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ORIGINAL ARTICLE

The path towards high-contrast imaging with the VLTI: the Hi-5 project

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Abstract The development of high-contrast capabilities has long been recognized as one of the top priorities for the VLTI. As of today, the VLTI routinely achieves contrasts of a few 10^{-3} in the near-infrared with PIONIER (H band) and GRAVITY (K band). Nulling interferometers in the northern hemisphere and non-redundant aperture masking experiments have, however, demonstrated that contrasts of at least a few 10^{-4} are within reach using specific beam combination and data acquisition techniques. In this paper, we explore the possibility to reach similar or higher

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contrasts on the VLTI. After reviewing the state-of-the-art in high-contrast infrared interferometry, we discuss key features that made the success of other high-contrast interferometric instruments (e.g., integrated optics, nulling, closure phase, and statistical data reduction) and address possible avenues to improve the contrast of the VLTI by at least one order of magnitude. In particular, we discuss the possibility to use integrated optics, proven in the near-infrared, in the thermal near-infrared (L and M bands, 3-5 μm), a sweet spot to image and characterize young extra-solar planetary systems. Finally, we address the science cases of a high-contrast VLTI imaging instrument and focus particularly on exoplanet science (young exoplanets, planet formation, and exozodiacal disks), stellar physics (fundamental parameters and multiplicity), and extragalactic astrophysics (active galactic nuclei and fundamental constants). Synergies and scientific preparation for other potential future instruments such as the Planet Formation Imager are also briefly discussed. This project is called Hi-5 for High-contrast Interferometry up to 5 μm.

Keywords Infrared interferometry · Integrated optics · VLTI · Hi-5 · PFI · Exoplanet · Exozodiacal dust · AGN

1 Introduction

Direct imaging is a powerful and historically important observing technique in astrophysics. From Galileo's lens to modern telescopes, scientific progress and discoveries have been guided by the development of imaging instruments with constantly improving angular resolution, sensitivity, and contrast. The contrast is defined here as the inverse of the dynamic range and represents the flux ratio (relative to the host star) of the faintest object that can be detected by the instrument at the 1-σ level. Current imaging instruments installed on 10-m class ground-based AO-assisted telescopes are strongly limited by contrast within a few resolution elements from the central star, typically 10^{-4} at the inner working angle (IWA, a few $0''.1$)

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to 10^{-5} at several λ/D from the central star (0″.5-1″.0, depending on the wavelength). Interferometric instruments can probe smaller spatial scales but at modest contrast (see Fig. 1). For instance, the VLTI achieves contrasts of a few 10^{-3} in the near-infrared with PIONIER (H band) and GRAVITY (K band) down to a few milliarcseconds (mas). Nulling interferometers installed in the Northern hemisphere and non-redundant aperture masking experiments have demonstrated better contrasts of a few 10^{-4} on baselines shorter than those available at the VLTI.

Developing high-contrast capabilities has long been recognized as one of the top priorities for future interferometric instruments and for the VLTI in particular e.g., [53, 68]. In the early 2000s, pushed by the need to prepare the way for future space-based infrared interferometric missions, a concept for such an instrument was designed and studied in detail for the VLTI [1]. This study established the instrumental constraints on fringe tracking and dispersion control to reach a contrast of 10^{-4}, approximately one order of magnitude better than what is achievable with the current and second-generation VLTI instrument suite. While this project did not materialize in an actual instrument, the key scientific questions that it intended to address remain, and high-contrast infrared interferometry is still nowadays the best option to answer them. New scientific questions that would benefit from such an instrument have also appeared in the last 10 years, making the case even stronger. Recent developments in VLT adaptive optics [24], interferometric data reduction the so-called

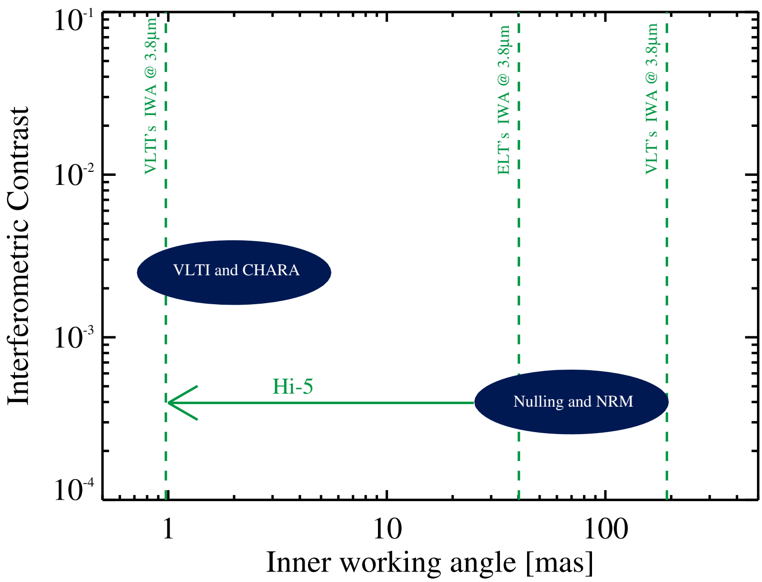

Fig. 1 Interferometric contrast as a function of inner working angle for current CHARA and VLTI instruments (i.e., FLUOR, MIRC, PIONIER, and GRAVITY) compared to that of nulling interferometers installed in the Northern hemisphere (i.e., PFN, DRAGONFLY, and LBTI) and non-redundant aperture masking (NRM) experiments (e.g., SPHERE/SAM). From left to right, the vertical dashed lines represent the inner working angle at 3.8 μm of the VLTI, the ELT, and the VLT (computed as $0.25 \times \lambda/b$ for the interferometers and as $2 \times \lambda/D$ for the single-aperture instruments)

Nulling Self Calibration or NSC, see [65], beam combination architecture [49], and integrated optics e.g., [6] offer new possibilities to bring the VLTI to the next level of high-contrast observations at small angular separation.

The Hi-5 (High-contrast Interferometry up to 5 µm) project has emerged from these developments. Initial studies are being funded by the H2020 OPTICON Joint Research Network and have officially started with a kickoff meeting held in Liège in October 2017. In this paper, we review first the heritage and lessons learned from other high-contrast interferometers (see Section 2). Then, in Section 3, we present the scientific motivations for a new high-contrast VLTI imaging instrument. Finally, in Section 4, we discuss key features that made the success of other high-contrast interferometric instruments and address possible avenues to improve the contrast achieved by the VLTI.

2 Heritage and lessons learned from other high-contrast long-baseline interferometers

2.1 Visibility interferometry

Several long-baseline infrared interferometers have been used in the past for science cases requiring high-contrast observations: VLTI/VINCI [45], IOTA/IONIC [7], CHARA/FLUOR [15], and VLTI/PIONIER [52]. These instruments all feature modal filtering provided by either single-mode fibers (VINCI and FLUOR) or integrated optics (IONIC, PIONIER). The measurement principle to reach high contrasts is based on absolute calibration of the squared visibilites obtained by scanning the interferogram faster than the atmospheric turbulence (coherence time), which can limit the observations to relatively bright targets in order to maintain the intended accuracy. The typical statistical uncertainty of the squared visibilities obtained with these instruments in good conditions is of the order of 1% and averages down to a few 0.1% after calibration of a complete observing sequence. This corresponds to achievable contrasts of a few 10^{-3}, which is sufficient to carry out surveys of hot exozodiacal dust e.g., [3, 25] or to search for bright stellar companions e.g., [56, 82]. In general, the contrast achieved by these concepts is/was limited by polarization errors [25, 51] and chromaticism of the beam combiner [18]. For VLTI/PIONIER, a special calibration procedure has been developed to mitigate the impact of polarization effects that occur in the VLTI optical train (external to PIONIER). This procedure consists in sampling sufficiently well the dependence of the polarization effect in the sky by observing several CAL-SCI-CAL sequences using different calibrators and science targets at a range of sky positions within one night and correcting for the well defined polarization behavior [25].

2.2 Closure phase

The closure phase is an important interferometric observable that is immune to atmospheric piston [71]. It corresponds to the phase of the triple product (or bispectrum). With current long-baseline interferometers such as VLTI/PIONIER and

CHARA/MIRC [72], contrasts of a few 10^{-3} can be achieved using closure phase [31, 50, 56]. Because of the sparse structure of the interferometric point spread function, the number and orientation of interferometric baselines are important to detect faint components. In addition, the angular separation of the component has to be resolved by at least some baselines, and in that case compensated by accurate interferometric measurements. The best median accuracy in closure phase that has been obtained with long-baseline interferometers is $\sim 0.5°$ for both VLTI/PIONIER and CHARA/MIRC in $\sim$ 30 min integration, while the best accuracy for a given measurement is 0.2°, which seems to be the current limit. This corresponds to contrast of a few 10^{-3}, which is currently the best detection limit for companions located within 25 mas [30, 81]. Fundamentally, closure-phase precision at high flux are limited by fringe tracking errors [42], which for 100 Hz bandwidths and 100 nm OPD residuals would be 0.002° in 10 minutes. However, many other instrumental challenges are likely to limit closure-phase uncertainties to about 10 times this limit even in an ideal instrument [33]. The loss of coherence caused by spectral smearing can also degrade the constrast for wide field-of-view but this effect can be reduced using high-spectral resolution observations (e.g., with VLTI/GRAVITY).

2.3 Nulling interferometry

A logical way to improve the contrast achieved by an interferometer is to suppress the stellar flux from the measured signal, similar to coronagraphy in single-pupil direct imaging, by employing destructive interference. The basic principle of this technique, first proposed by [9], is to combine the beams in phase opposition in order to strongly reduce the on-axis starlight while transmitting the flux of off-axis sources located at angular spacings given by odd multiples of $0.5\lambda/B$ (where B is the distance between the telescope centers). The high-angular resolution information on the observed object is then encoded in the null depth, which is defined as the ratio of the flux measured in destructive interference and that measured in constructive interference. The advantage of obtaining null depth measurements is that they are more robust against many kinds systematic errors than visibility measurements and hence lead to a better accuracy e.g., [14].

A number of nulling interferometers have been deployed at US observatories over the last twenty years or so, both across single telescopes and as separate aperture interferometers. These include the BracewelL Infrared Nulling Cryostat BLINC, [38], the Keck Interferometer Nuller KIN, [84], the Palomar Fiber Nuller PFN, [65], the Large Binocular Telescope Interferometer LBTI, [39], and DRAGONFLY/GLINT on Subaru/SCEXAO [76]. Working largely at mid-infrared wavelengths (8-14 μm), where dust in the habitable zones of stars is prominent, and where phase instability is more tractable than at shorter wavelengths, a variety of techniques have been demonstrated on-sky, allowing constraints to be set on exozodiacal emission around a number of nearby stars. Much was learned about instrumental limitations over the course of this work, but mid-IR experiments are inevitably limited by the high background radiation. On the other hand, two on-sky nullers have operated successfully at near-IR wavelengths, where the background is less of an issue, but where phase fluctuations are more problematic. High null depth accuracies were reached with both the PFN and DRAGONFLY/GLINT at these short wavelengths (approaching 10^{-4} in the best case) due to a combination of factors: the ability to use single mode fibers (PFN) or integrated optics (GLINT), the use of the telescope's extreme adaptive optics system as a cross-aperture fringe tracker, and the introduction of a significantly improved technique for null-depth measurement, i.e., null self-calibration. In this technique, fine null stabilization is abandoned in favor of using the statistics of the null depth fluctuations to separate the instrumental and astrophysical null depth contributions, in what is essentially an interferometric analog of dark speckle techniques. In fact, null self-calibration significantly relaxes the constraints on the terms contributing to the null error budget, such as the intensity and phase balance, and thus allows for a less constrained nuller design. Even so, high symmetry and stability remain the essential starting points for any high-accuracy nulling interferometer.

3 Science case of VLTI high-contrast interferometry

3.1 Planet formation and young giant planets

Planets form in the disks around young stars. During the first few million years, these disks are optically thick and the planetary cores are deeply embedded in the disk material. As the planets interact with the disk and the disk dissipates, the planets should become observable through direct imaging. Most planet searches with interferometry in young systems have been conducted using the non-redundant aperture masking (NRM) technique e.g. [47]. However, it has been found that asymmetric emission from the optically thick circumstellar disk can introduce strong phase signals, which can lead to false companion detections see simulations in [77, 90]. A high-contrast thermal near-infrared imager at the VLTI will mitigate these problems by using 10 to 20 times longer baselines than single-aperture NRM interferometry, allowing us to better separate the planet emission from the disk emission. Determining the occurrence rate of giant planets at young age and smaller angular separation can provide critical constraints on planet formation theories and evolution models e.g., [4, 74, 85]. In that regard, the thermal near-infrared is a sweet spot to directly detect the photons of self-luminous or irradiated close-in and young ($<$100 Myr) giant planets (see Fig. 2). Surveys of nearby young stellar moving groups could detect new giant planets at angular distances inaccessible by current instruments and future ELTs. Monte-Carlo simulations are currently being performed to estimate the number of new detections that can be expected for different levels of contrasts. In addition, with a contrast of 10^{-4}, previously-known giant exoplanets detected by radial velocity (e.g., τ Boo b, Gliese 86d) can be resolved and characterized. Preliminary estimates indicate that 5 (resp. 15) known exoplanets could be directly observed for the first-time with a VLTI instrument achieving a contrast of 10^{-4} (resp. 10^{-5}). Low-resolution spectroscopic observations of such planets in the thermal near-infrared are ideal to derive the radius and effective temperature as well as providing critical information to study the non-equilibrium chemistry of their atmosphere via the CH_4 and CO spectral features. The possibility to directly detect exoplanets around nearby low-mass stars (e.g., Proxima b) will also be investigated during the Hi-5 study.

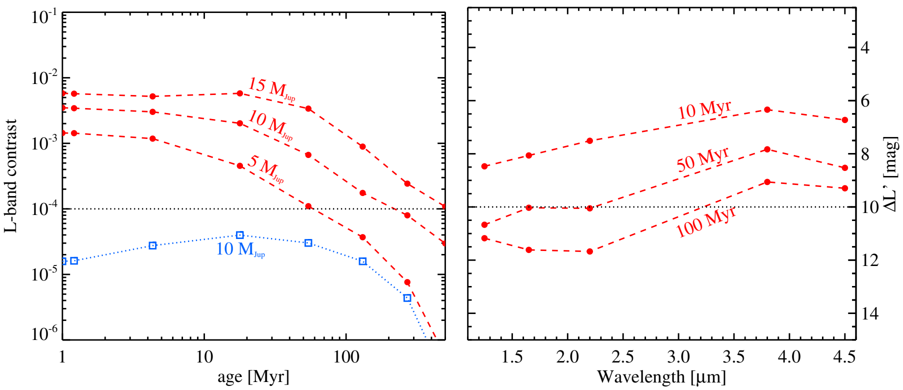

Fig. 2 *Left*: Predicted L-band planet-star contrast for a 1-$M_\odot$ star as a function of age and given for different planet masses red circles, BT-Settl models, [4]. The lower blue line shows the contrast predicted for the "cold start" model [85] and a 10-M_{Jup} planet. *Right*: contrast between a 10-M_{Jup} planet and a 1-$M_\odot$ star as a function of wavelength, showing that the L and M bands provide a better contrast compared to shorter wavelengths and especially for adolescent planets (∼100 Myr). The dashed horizontal line represents the targeted contrast for Hi-5 (i.e., 10^{-4} or 10 magnitudes)

3.2 Exozodiacal disks

Exozodiacal dust emits primarily in the near-infrared to mid-infrared where it is outshone by the host star. For instance, in the solar system, the zodiacal dust amounts to 5×10^{-5} of the stellar flux at 10 μm and how this value compares to other systems is currently poorly constrained. Due to the small angular scales involved (1 AU at 10 pc corresponds to 0.1 arcsec), the angular resolution required to spatially disentangle the dust from the stellar emission currently requires the use of interferometry. Thus, exozodis have so far mostly been observed at the CHARA array and the VLTI in the near-infrared [2, 3, 19, 25, 26] and at KIN and the LBTI in the mid-infrared [20, 27, 66, 69]. These observations reached contrasts of a few 10^{-4} to a few 10^{-3}, leading to vital statistical insights into the occurrence rates of exozodis as a function of other properties of the systems such as the presence of cold, Kuiper belt-like dust disks or stellar age and spectral type. The main challenge at the moment is linking the near-infrared and the mid-infrared detections, which critically constrains the systems' architectures and the properties and origin of the dust. However, so far no connection between the detections in the two wavelength ranges has been found. A high-contrast instrument operating in the thermal near-infrared like Hi-5 is the ideal tool to trace the spectral energy distributions of near-infrared detected exozodis toward longer wavelengths and of mid-infrared detected exozodis toward shorter wavelengths in order to connect the two and to understand non-detections in one wavelength range in the light of detections in the other. Moreover, no sensitive interferometric instrument operating in the thermal near-infrared is available in the Southern hemisphere so far. MATISSE is not designed for high-contrast observations and will be limited to the characterization of the brightest systems already detected in the near-infrared. The high contrast thermal near-infrared capabilities of Hi-5, together with the efficiency increase due to the simultaneous use of four telescopes already demonstrated at the VLTI with PIONIER, will allow for a large survey for habitable zone dust in the Southern hemisphere. Estimates performed during the GENIE study suggested that a contrast of a few 10^{-4} will be enough to study habitable zone dust down to levels approximately 50 times as dense as the Solar zodiacal cloud [1]. This will significantly improve our understanding of the occurrence rates of systems harboring Solar system like exozodiacal dust and increase the currently very short list of such systems to be studied in detail.

3.3 Stellar physics: binarity accross the HR diagram

Optical interferometry has been used to complement AO assisted imaging survey of stars to estimate the multiplicity fraction. For instance, [82] have shown that virtually all massive stars are in multiple system, thanks to a distance-limited survey of close-by massive stars. Extending this result to other class of stars is still to be done, and one of the limitation is contrast: companion detection requires both inner-working angle and detection depth. Apart from multiplicity fraction, another interest of binarity study is determination of fundamental parameters such as dynamical masses or distances. Spectroscopy is currently more sensitive than interferometry, so the stellar mass is only known to the sine of the inclination of the orbit. Direct imaging and follow up of the companion allows to estimate the true stellar mass. For example, companions around Cepheid pulsating stars are difficult to detect and only the brightest companions are detected using near-infrared interferometry in the 10 mas separation / 5×10^{-3} contrast regime [28, 29]. The perspective of spectroscopic radial velocities of the companion (using UV spectroscopy) and interferometric visual orbit opens the possibility for independent distance to Cepheids, rivaling Gaia in term of distance accuracy (Gallenne et al., in preparation). Even if the L band is not optimum to detect hot Cepheids companion, an ten-fold improvement in contrast compared to current H-band instrument will still lead more detections.

3.4 Extragalactic astrophysics

Most of the physical processes in Active Galactic Nuclei (AGN) take place on scales of a few parsec or less (i.e. $\lesssim$ 100 mas for the nearest galaxies). Hence, it requires interferometic methods to resolve the relevant scales. AGN are "faint" for infrared interferometry, with fluxes of $F_K < 70$ mJy ($K > 10$ mag) in the near-infrared, and $F_N < 1$Jy ($N > 4$ mag, with a few exceptions) in the mid-infrared. Additionally, AGN spectra are very red and they often appear extended in the optical, leading to limitations for fringe tracking and poor AO correction. Nevertheless, interferometry of several AGN with the VLTI and the Keck Interferometer has shown that their dust distributions are compact, with sizes roughly scaling with the square root of the intrinsic luminosity e.g. [11, 46, 88]. The few better resolved sources reveal a two component structure, with a central disk and an emission extending in the polar direction e.g. [40, 55, 89]. However, the number of AGN observable by current instruments is very limited and most sources only appear marginally resolved, especially toward shorter wavelengths. Further progress in our understanding of AGN can hence only be expected from an instrument providing *high accuracy visibility* (or high-contrast) measurements as well as a *high sensitivity*. This will allow to better constrain larger samples of marginally resolved AGN, especially if also the ATs on the longest baselines can be used. Furthermore, by combining interferometric with reverberation measurements, direct distances to such sources can be determined [41], with the possibility to independently constrain the Hubble parameter.

4 Improving the contrast of the VLTI

4.1 Beam combination strategy

Over the past few years, several new interferometer architectures have been proposed in order to improve the performance and robustness against perturbations of nulling interferometers. In particular, [49] proposed an architecture concept that produces closure-phase measurements from nulled outputs. More recently, [61] proposed the idea of "kernel nulling" as a more generalized approach. The idea behind these concepts is to combine the outputs of a first nulling stage in a second mixing stage, with the goal of creating an output signal more robust against imperfect cophasing of the incoming stellar light. Another interesting idea proposed by [59] is to use a diffraction grating to adjust the phase of the light and produce achromatic destructive interference at the tip of single mode fiber. Finally, one can also consider an interesting new idea of symmetric beam combination scheme that is insensitive to polarization states i.e., the Cross Cuber Nuller, [37]. The application of these techniques to the VLTI will be investigated during the Hi-5 study.

4.2 Integrated optics

Integrated optics (IO) is a key component of current high-contrast VLTI interferometers such as PIONIER (H band) and GRAVITY (K band). Indeed, thanks to their single-mode properties, IO components deliver a much more stable instrumental transfer function than equivalent bulk-optics beam combiners. Significant efforts have been made over the past few years to make IO components at longer wavelengths and the technology has now reached a level of maturity sufficient for astronomical considerations. In the thermal near-infrared, recent studies have been targeting the development of components with ultrafast laser inscription in mid-infrared-transparent glasses. Ultrafast laser inscription (ULI) is a versatile technique using highly focused pulses from a femtosecond laser to induce permanent structural modifications in a large variety of glasses see [32]. The modifications are responsible for localized changes of the refractive index, which can be used to manufacture photonic devices based on waveguides. Remarkably, three dimensional structures can be written by scanning the glass samples under the laser focus. Particularly interesting for thermal near-infrared interferometry is the processing of chalcogenide glasses such as Gallium Lanthanum Sulfide [80] or Germanium Arsenic Sulfide [16], which have transparency windows extending to a wavelength of about 10 μm. Waveguides with propagation losses at the 0.7-0.9 dB/cm level are routinely manufactured with ULI techniques. Photonic building blocks such as Y-junctions [80] and 2x2 directional couplers have been demonstrated [5]. Couplers similar to the latter component were recently characterized in the L-, L′- and M-bands, demonstrating high broadband contrasts, low spectral phase distortion, and 30% to 60% measured throughput [86, 87]. More advanced components, allowing the combination of several telescopes, have also been manufactured and tested. The first component was a 3-telescope N-band combiner based on cascaded Y-junctions with three-dimensional avoidance of waveguide cross-overs [80]. More recently, a 2-telescope ABCD combination unit [6] and a 4-telescope beam combiner based on Discrete Beam Combiner geometry [70] were manufactured with ULI and tested interferometrically with monochromatic light at 3.39 μm [23]. Both components showed that retrieval of complex visibilities with high signal to noise is possible at relatively low illumination levels.

An alternative to ultrafast laser inscription to fabricate integrated optics beam combiners is the use of classical methods, such as Ti:indiffusion inside electro-optic crystals. These waveguides are interesting as the refractive index of the material, and therefore the phase of the propagating optical beam, can be modified by the application of an external voltage. In the particular case of Lithium Niobate crystals, the transparency window reaches 5.2 μm allowing to cover L and M bands. Using this technology, phase and intensity modulators [36], achieving on-chip fringe scanning, fringe locking and high-contrast interferometry have been demonstrated using **a monochromatic laser** at 3.39 μm [57]. Concepts such as active 2T ABCD [35] and 3T AC [58] infrared beam combiners have been validated experimentally. However, propagation losses in these systems are currently too high (typically 5 dB/cm). Therefore, novel methods such as ULI presented above, but developed in electro-optic crystals, are being tested for waveguide fabrication, showing low propagation losses (1.5 dB/cm) in the first prototypes [75]. Finally, note that two-dimensional photolithography on a platform with Ge,As,Se and Ge,As,S based glasses offsets the potential for less than 0.5dB/cm losses in mm-scale chips tolerant of low bend-radius [44]. Comparing these different technologies and how their technical specifications translate into the usual interferometric metrics (e.g., sensitivity, limiting magnitude, instrumental contrast) will be one of the major goals of the Hi-5 system study.

4.3 Fringe tracking

Phase-referenced interferometers require accurate and robust fringe tracking for sensitive background-limited observations and high-contrast imaging. Studies performed more than a decade ago concluded that closed-loop OPD residuals of no more than $\sim$ 10 nm RMS are required to reach contrasts of a few 10^{-4} at 3.8 μm [1, 83]. More recently, new pre-processing and post-processing techniques have emerged to significantly relax these constraints. A promising pre-processing technique currently under investigation uses a dual fringe tracking and low-order adaptive optics concept based on a combination of non-redundant aperture interferometry and eigen-phase in asymmetric pupil wavefront sensing e.g., [60]. Applied to the VLTI with the NAOMI adaptive optics system functioning on the ATs, this approach could in theory enable L-band contrasts of a few 10^{-6} for bright stars [61, $m_{L'}$ $\sim$3,] and fringe tracking sensitivity down to H$\simeq$12 at the level of $\sim$300 nm RMS in most seeing conditions. Currently, the GRAVITY fringe tracker achieves a limiting magnitude of K$\simeq$7.0 with the ATs and K$\simeq$10.0 with the UTs in single-field mode, with performance levels of 200-300 nm RMS, depending on conditions. Under very good conditions, 1 to 2 deeper magnitudes can be achieved but generally at the expense of stability.

Regarding post-processing techniques, a new statistical data reduction method, called null self calibration (NSC), has recently shown that it is possible to reach contrasts down to 10^{-4} with significantly relaxed instrumental constraints [34, 65]. For instance, a contrast of a few 10^{-4} has been achieved with the LBTI despite closed-loop OPD residuals of approximately 400 nm RMS [21, 67]. The idea of this data reduction technique is to use the full distribution of null measurements and fit models of null histograms to the observed data. The great advantage of this approach is to be immune to errors on the nulling setpoint, which is one of the major issues of ground-based nulling interferometers. Currently only applicable to two-telescope interferometers, this method has to be generalized for more telescopes in order to be used with the VLTI.

Another limiting factor of current high-contrast long-baseline interferometers is the phase chromaticism induced by random fluctuations in the water vapor differential column density above each aperture (or water vapor seeing). This component of the OPD is not correctly tracked at the wavelength of the science channel when this one operates at a wavelength different from that of the fringe sensor. The impact of this effect on infrared interferometry has been addressed extensively in the literature, either in a general context [12] or applied to specific instruments that include phase-referenced modes using K-band light such as VLTI/MIDI [62, 64, 78], the KIN [13], and the LBTI [22]. A possible implementation to mitigate this effect could be to have two separate fringe trackers: a fast one operating at short wavelength to correct for fast OPD variations and a slow one operating at the same wavelength as the science channel to correct for water vapor seeing. This effect will be seriously considered in the context of the Hi-5 study.

4.4 Limiting magnitude

One important metric of an interferometer is its limiting magnitude, which is related to different instrumental parameters such as aperture size, throughput, and scan speed. For instance, the limiting magnitude of VLTI/PIONIER is constrained toward faint targets because the fringes are tracked internally on the science data and the scan speed needs to be large enough compared to the coherence time in order to minimize the degrading effects of atmospheric turbulence during a scan. In order to track the fringes, at such short integration times the (correlated) flux must be high enough to reach a good signal-to-noise ratio in each single scan. The problem is similar for phase-referenced instruments, which suffer from significant performance degradation for faint stars because a slower acquisition rate has to be used. Reduced fringe tracking performances have a direct impact on the achievable contrast, which may vary by several orders of magnitude as recently quantified in the Hi-5 framework [61]. Finally, it is worth noting another way to relax the constraints on scan speed by using real-time data from accelerometers attached to the optical train [8] and/or adaptive optics wave-front sensing [79].

5 Synergies with other instruments

Hi-5 will be complementary to several future high-angular resolution instruments operating in the thermal near-infrared as described below.

- MATISSE [54, Multi AperTure mid-Infrared SpectroScopic Experiment,63] is the second-generation thermal near-infrared and mid-infrared spectrograph and imager for the VLTI. MATISSE will provide a wide wavelength coverage, from 2.8 to 13 μm, associated with a milli-arcsecond scale angular resolution (3 mas in L band; 10 mas in N band), and various spectral resolutions from R $\sim$30 to R$\sim$5000. In terms of performance, many instrumental visibilities were measured in laboratory conditions during the test phase. Those measurements were performed with a very bright artificial IR source to estimate the instrumental contribution to the accuracy without being limited by the fundamental noises. Such a source would have an equivalent flux, if observed with the UTs, of 20 to 70 Jy in N-band, 400 Jy in M-band, and 600 Jy in L band. Computed over 4 hours in LM band and 3 days in N band, the absolute visibility accuracy is lower than 0.5 percent in L band, 0.4 percent in M band, and 2.5 percent in N band, on average over the corresponding spectral band. Those promising results are extensively described in internal ESO documents written by the MATISSE consortium (private communication with A. Matter). Eventually, the on-sky tests (commissioning), starting in March 2018, will provide the real on-sky performance (sensitivity, accuracy) of MATISSE, which will include the effects of the sky thermal background fluctuations, the atmospheric turbulence, and the on-sky calibration.
- ELT/METIS [10] is the Mid-infrared E-ELT Imager and Spectro-graph for the European Extremely Large Telescope. METIS will provide diffraction limited imaging and medium resolution slit spectroscopy in both the thermal near-infrared and the mid-infrared (5-19 μm) ranges, as well as high resolution (R = 100000) integral field spectroscopy from 2.9 to 5.3 μm. Assuming a collecting aperture of 39 m in diameter, METIS will have approximately six times more collecting power than the VLTI but five times poorer angular resolution. The two instruments will therefore probe complementary parameter spaces for a given wavelength. Alternatively, METIS will provide an angular resolution in the near-infrared similar to that of Hi-5 in the thermal near-infrared (see Fig. 1). VLTI/Hi-5 will hence provide complementary high-contrast observations to characterize the observed planets and circumstellar disks. In particular, a VLTI instrument can make use of less-solicited telescopes such as the ATs to follow-up in the thermal near-infrared new ELT/METIS discoveries. Finally, note that, while METIS will obviously have the sensitivity to detect exozodis, it will hardly be possible to unambiguously detect extended sources within 3 lambda/D ($\sim$60 mas at L band, $\sim$150 mas at N band). Known hot and warm exozodis are

all located much closer than that. Blackbody considerations also puts the dust closer than that for a G2V star located at 10 pc (∼15 mas for 800K dust better probed at L band and ∼100 mas for 300K dust better probed at N band).

- PFI Planet Formation Imager, [43, 48, 73] is currently a science-driven, international initiative to develop the roadmap for a future ground-based facility that will be optimized to image planet-forming disks on the spatial scale where the protoplanets are assembled, which is the Hill sphere of the forming planets. The goal of PFI will be to detect and characterize protoplanets during their first ∼ 100 million years and trace how the planet population changes due to migration processes, unveiling the processes that determine the final architecture of exoplanetary systems. With ∼ 20 telescope elements and baselines of ∼ 3 km, the PFI concept is optimized for imaging complex scenes at thermal near-infrared and mid-infrared wavelengths (3-12μm) and at 0.1 milliarcsecond resolution. Hence, Hi-5's mission will be "explorative", while PFI's mission will be to provide a comprehensive picture of planet formation and characterization (resolving circumplanetary disks). Hi-5 and PFI will also share many common technology challenges, for instance on thermal near-infrared beam combination, accurate/robust fringe tracking, and nulling schemes.
- FKSI Fourier-Kelvin Stellar Interferometer, [17] is a concept for a small structurally connected space-based infrared interferometer, with a 12.5-m baseline, operating from 3 to 8 μm or possible 10 μm, passively cooled to 60 K, operating primarily in a nulling (starlight suppressing) mode for the detection and characterization of exoplanets, debris disks, and extrasolar zodiacal dust levels. It would have the highest angular resolution of any infrared space instrument ever made with a nominal resolution of 40 mas at a 5 μm center wavelength. This resolution exceeds that of Spitzer by a factor of 38 and JWST by a factor of 5. Relatively little work has been done since 2010 on FKSI, due to funding limitations. However, within the past year or so there has been renewed interest at NASA regarding missions with a lifecycle cost of less than one billion dollars. In addition, there is increasing interest at NASA for distributed spacecraft mission concepts, as well as novel low-cost mission concepts, either for a specific astrophysics observation/measurement or to advance technologies, with some science. Hi-5 and FKSI will share common technology challenges such as thermal near-infrared beam combination and accurate/robust fringe tracking.

6 Summary and conclusions

The VLTI currently achieves contrasts of a few 10^{-3} in the near-infrared and second-generation instruments are not designed to do better. Achieving deeper contrasts at small inner working angles is however mandatory to make scientific progress in various fields of astrophysics and, in particular, in exoplanet science. On the VLTI, gaining one order of magnitude (i.e., contrasts of at least a few 10^{-4}) is today within reach as demonstrated with ground-based nulling interferometers in the northern hemisphere and non-redundant aperture masking instruments. In addition, integrated optics, a key technology that made the success of PIONIER (H band) and

GRAVITY (K band), is now coming to maturity for the the thermal near-infrared (L and M bands), a sweet spot to image young giant exoplanets. New ideas have also emerged to improve the contrast of long-baseline interferometers (i.e., combining nulling and closure phase, kernel nulling, advanced fringe tracking, high-dispersion interferometry). These new possibilities for high-contrast imaging will be investigated in the context of the Hi-5 study, which will particularly explore the limits of exoplanet detection from the ground with existing interferometers. Besides the clear scientific motivation, a new high-contrast VLTI imaging instrument will serve as a key technology demonstrator for future major interferometric instruments such as PFI and TPF-I/DARWIN-like missions. Technology demonstration will include fringe tracking, advanced beam combination strategies, thermal near-infrared integrated optics components (which greatly reduce the complexity of the instrument), and four-telescope statistical data reduction.

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